(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(54) Title: PROCEDURE FOR CONTROLLING IC ENGINES

(57) Abstract: A control assembly is described in relation to the control of a non linear system by a linearly controlled arrangement. In particular an event based control system is employed to overcome the problem of non linear torque control in spark ignition internal combustion engines. In addition to the torque control a means for controlling the engine efficiency is also described. Control of engine efficiency results in improved engine response to load disturbances when the engine is in the idle condition. The facility to vary the efficiency of an engine is also beneficial in situations where the thermal output of the engine is desired to be increased. Typically these occur after start up when it can be desirable to quickly heat up the vehicles catalyst or passenger compartment. The employment of a linear control system also leads to significantly reduced calibration times in the development stage of the engine.

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1 **Procedure for controlling IC engines**

2

3 This invention relates to the provision of a means of

4 providing linear control of a non-linear system. In

5 particular it relates to the provision of a system and

6 method for removing the non-linear nature of the torque

7 control problem in spark ignition internal combustion

8 (gasoline) engines and for allowing the control of engine

9 efficiency as well as torque. More specifically there is

10 described a method of using a set of signal manipulation

11 techniques at the (signal) input and output of the

12 gasoline engine that allows the use of standard linear

13 control techniques to accurately control both engine

14 torque and efficiency (or, equivalently, torque reserve).

15

16

17 Technical Background:

18 Traditionally, the torque output of a spark ignition

19 gasoline engine has been controlled directly by the

20 driver moving the throttle in the air intake path,

21 allowing more or less air to be inducted into the

1   cylinder with each induction stroke. The function of the

2   carburettor or fue. injection system being to add fuel to

3   the air such that the in-cylinder combination has a fixed

4   mass   ratio.   The   spark   timing   would   be   controlled

5   (mechanically   or   electronically)   with   the   goal   of

6   obtaining   the   maximum   torque   possible   from   each

7   combustion event.

8

9   More   recently,   it   has   become   commonplace   to   move   the

10   spark   timing   away   from   that   which   gives   the   optimal

11   torque production in certain engine operating modes. Most

12   particularly the idle mode, a more complete discussion of

13   this application is given further in this document. In

14   order for the operating efficiency to be reduced whilst

15   still   producing   the   same   overall   net   torque   from   the

16   engine,   the   airflow   into   the   engine   must   be   increased.

17   For the engine controller to do this there must either be

18   an   electronically   controlled   parallel   airpath   into   the

19   engine or an electronically controlled main airpath into

20   the   engine.   Prior   art   techniques,   whilst   explaining   the

21   various advantages of this reduction in efficiency, have

22   not explained explicitly how to achieve this seamlessly

23   in practice. Practical realisation of the reduction in

24   efficiency is straightforward to achieve if the desired

25   change in efficiency is slowly changing and the engine is

26   at one operating point, however if the desired change is

27   quickly varying or if the operating point of the engine

28   is   rapidly   changing   then   prior   art   methods   are   very

29   difficult to implement because of the nonlinear nature of

30   the   engine   system.   This   is   the   case   for   the   three

31   examples given in this document, the techniques described

32   herein enabling greatly improved control in these cases.

33   The   following   section   expands   on   the   particular

1 requirements and difficulties of the idle control

2 problem.

3

4 The control of the speed of gasoline engines when

5 operating in the idle condition whilst keeping the rate

6 of fuel usage of the engine as low as possible presents a

7 number of difficulties. The speed of a gasoline engine at

8 idle is affected by many forms of disturbance; cyclic

9 variability in torque production, varying friction

10 characteristics of the engine and mechanical loads from

11 accessories such as the alternator, power steering pump

12 and air conditioning pump. The magnitude of the accessory

13 disturbances in particular has increased as the level of

14 standard equipment in vehicles increases. Thus on a cold

15 morning a driver may enter his/her car, start the engine,

16 and with the engine in idle condition, switch on the

17 front and rear electrical demisters, move the electric

18 chair to a more suitable condition, turn on the electric

19 chair heater and then make several lock-to-lock steering

20 movements to get out of the parking spot. The power

21 demand of the steering is at its highest when the vehicle

22 is stationary. All of the energy drains must be countered

23 by an increase in torque from the engine but without

24 perceivable changes in idle speed. To reject the effect

25 on speed of these disturbances, modern engines use

26 electronic engine control units and feedback control

27 techniques to keep the speed constant. Whilst in idle

28 mode, the airflow into the engine is controlled by the

29 engine management system using a secondary throttle,

30 (also known as an idle speed control valve (ISC) or air

31 bypass valve (ABV)) in parallel with the primary, driver

32 controlled throttle, or an electronically controlled main

33 throttle. Because the speed of response of this actuator

34 is slow (due to the time for the effect of the change in

4

1 secondary throttle, or electronic main throttle, position

2 to propagate through the manifold and affect the air

3 inducted into the cylinder), the spark timing is also

4 used. It being retarded from the point of optimal torque

5 production to a point that allows some torque reserve

6 which can be available for almost instant rejection of

7 torque disturbances. The further away from the timing for

8 optimal torque production that the engine is operated at,

9 the more torque reserve the engine/controller has but the

10 more fuel is used to keep the engine at the desired

11 speed.   Methods   for   controlling   the   speed   use   a

12 measurement of speed and control the secondary throttle

13 or   electronic   main   throttle,   and   spark   timing.   The

14 effectiveness of the idle control mechanism will dictate

15 the idle speed set point of the engine. A poor controller

16 will have to have a high idle set point so that low side

17 excursions do not cause the engine to stall. A figure

18 used by the industry is that every 100rpm decrease in

19 idle speed setpoint is approximately equivalent to one

20 mile per gallon improvement in fuel economy. Note again

21 that a poor idle controller will have to operate far from

22 optimal   spark   timing   to   achieve   the   torque   reserve

23 necessary for stable idle. This alone can increase the

24 fuel used during idle by a factor of 2 or 3. Clearly an

25 effective controller which can operate close to optimal

26 spark timing and at a lower speed will make significant

27 fuel economy improvements.

28

29 Prior art techniques have traditionally relied on simple

30 linear   controllers   (typically   of   the   proportional   +

31 integral type) to control the spark and bypass valve in

32 response to a speed variation. These controllers have to

33 be calibrated at many different operating points so that

34 although   the   controller   structure   is   simple,   the

1 parameters that the controller uses will be based on
2 large look-up tables and the control action will have
3 many special case responses which again are the result of
4 many man months of calibration effort. The reason for the
5 inadequacy of this linear technique is that the system
6 itself is very non-linear. If the speed of the engine
7 drops as a result of an unanticipated load, then the
8 effect of the next spark will be different because we are
9 now at a different operating point, less torque will be
10 generated and thus the size of the excursion will
11 increase. Many researchers have tried more complicated
12 linear control techniques which have the advantage that
13 they may overcome some of the effects of the nonlinearity
14 and   the   disadvantage   that   they   are   generally
15 significantly harder to calibrate for the areas where a
16 variation   in   controller   parameter   is   necessary.
17 Conversely,   some   non-linear   techniques   are   available
18 which will enable the control engineer to take account of
19 some or all of the non-linear characteristics of the
20 engine when designing the controller. However these non-
21 linear techniques are very cumbersome in the design stage
22 so that designing a controller is possible but designing
23 a good controller is very difficult.
24
25 In a more general form the technique for making linear
26 the   control   of   torque   and   operating   efficiency
27 (equivalently,   torque   reserve)   could   be   used   in   other
28 engine operating modes. Two examples are:
29
30 1) in   the   transition   from   homogeneous   to   stratified
31   charge mode in direct injection gasoline engines it
32   will be desirable to increase the manifold pressure
33   before the switch without increasing the torque. This
34   can   be   done   by   reducing   the   efficiency   of   the

1   combustion   which   is   easily   effected   using   this
2   technique
3
4   2) When preparing for the deactivation of one or more
5   cylinders in more general engine types it is desirable
6   to increase the torque reserve so that when the one or
7   more   cylinders   is/are   deactivated,   the   remaining
8   active cylinders can rapidly increase their torque to
9   keep the overall torque output of the engine at the
10   desired level. This functionality is easily achievable
11   using the technique presented here.
12
13 In   both   of   these   examples   the   required   change   in
14 efficiency   is   rapid,   existing   techniques   being   very
15 difficult to implement successfully in these cases.
16
17 It is an object of the present invention to provide a
18 control system and method that allows the use of standard
19 linear control techniques to control an essentially non-
20 linear system such as a gasoline engine.
21
22 It   is   a   further   object   of   the   present   invention   to
23 improve a gasoline engine's response to load disturbances
24 in the idle condition.
25
26 It is a still further object of the invention to provide
27 a means of varying the operating efficiency of a gasoline
28 engine in order to increase the thermal energy output of
29 the engine in specified circumstances.
30
31 It is a still further object of the present invention to
32 provide   a   control   system   and   method   which   requires
33 significantly less calibration time in the development
34 stage than prior techniques.

1

2 According to the present invention there is provided a

3 control assembly for a non linear system comprising non-

4 linear map interface means connecting input and output

5 points of the non linear system to a linear control

6 arrangement.

7

8 The non-linear system may, for example, be a spark

9 ignition gasoline engine.

10

11 The control assembly may be the idle speed control system

12 or engine management system of the gasoline engine.

13

14 Controlled inputs to the engine are preferably spark

15 timing and secondary throttle, or electronic main

16 throttle, settings and measured engine outputs include

17 engine speed and manifold pressure.

18

19 Further according to the present invention there is

20 provided an internal combustion engine management system

21 which provides control of engine input parameters in

22 accordance with an anticipated load disturbance resulting

23 from the operation of engine auxiliary components in

24 advance of the application of the said load.

25

26 Preferably, but not necessarily, the engine management

27 system controls both the engine input parameters and the

28 load disturbing components such that engine output torque

29 may be increased in accordance with increased load

30 application.

31

32 Still further according to the present invention there is

33 provided an internal combustion engine management system

34 arranged for allowing the operation of the engine at

1 close to optimal efficiency in the idle condition, the
2 system being further arranged so as to decrease the
3 operating efficiency of the engine and increase the
4 thermal output of the engine in predetermined conditions.
5
6 Increased thermal output may be required in a cold start
7 situation where it is desirable to achieve normal
8 operating temperature as quickly as possible.
9
10 Alternatively, increased thermal output may be required
11 in a cold start situation to allow the catalyst to reach
12 operating temperature as quickly as possible.
13
14 Alternatively increased thermal output may be required in
15 order to maximise the heat output of an associated
16 heating system.
17
18 Embodiments of the present invention will now be
19 described by way of example with reference to the
20 accompanying drawings:
21
22   Figure 0 is a general representation of a method for
23   enclosing a non-linear engine system using the
24   method described herein to produce a resulting
25   system which is linear or almost linear from input
26   to output;
27   Figure 1a is a diagram illustrating the effect of
28   spark timing or torque production for a given engine
29   speed and manifold pressure (or, equivalently, air
30   flow);
31   Figure 1b is a diagram illustrating the map for
32   spark advance required to give desired torque
33   production for a given engine speed and manifold
34   pressure (or, equivalently, air flow);

1   Figure 2a is a representation of the effect of the

2   secondary throttle position on the manifold air

3   pressure and thence the distance from peak torque

4   (at any operating point); and

5   Figure 2b is a representation illustrating the use

6   of the inverse map for representing the non-linear

7   part of the manifold dynamics, such that the second

8   input-output pair also becomes a linear system (at

9   any operating point).

10

11 Disclosure of the invention:

12 The present invention overcomes the shortcomings

13 described above of prior art methods by utilising a

14 control scheme that includes signal manipulation

15 techniques to make a more easily controllable system. The

16 method, as illustrated in Figure 0, creates an overall

17 system which is not only linear, or almost linear,

18 (depending on implementation) from (new) inputs to

19 outputs, but also creates another synthetic output which

20 allows the direct on-line control of the efficiency, or

21 equivalently torque reserve, of the engine. Thus by

22 'wrapping' the engine using the method described, the

23 engine will appear linear, or almost linear, and

24 intuitive at all operating points likely to be met in the

25 idle regime. This has the advantage of allowing advanced

26 linear control techniques to be used, which can extract

27 more performance from the controller for less calibration

28 time. The nature of the interfacing method is such that

29 the parameters which characterise it can be identified

30 from a small number of test operations taking, compared

31 to prior art techniques, a vastly reduced amount of

32 testing time. The second output (MBT-T) being a measure

33 of efficiency of the engine allows the engineer to design

34 controllers which will allow very efficient operation

1   when few disturbances are anticipated, and quickly move

2   to a less efficient point when load disturbances are

3   imminent. Alternatively it enables smooth transitions

4   between engine operating modes by matching the torque

5   production either side of the transition.

6

7   More specifically, the torque produced by the combustion

8   event of a S.I. engine (assuming constant air-fuel ratio)

9   is a static function of the amount of charge in the

10   cylinder, the engine speed (spd) and the spark timing, or

11   equivalently, the manifold pressure (MAP) at the end of

12   the induction stroke, the engine speed and the spark

13   timing. This is illustrated in figure 1a. If the spark is

14   not allowed to go beyond the point of optimal torque then

15   the torque map can be inverted as suggested in figure 1b.

16   This inversion allows the engine management system to

17   control the torque production from the combustion event

18   directly, the relationship between torque and speed being

19   a linear one so the control design problem is

20   significantly easier.

21

22   More specifically, the spark timing, in conjunction with

23   a measurement of the manifold pressure at the end (or

24   some other portion) of the induction stroke of the

25   cylinder for which the next combustion event occurs, and

26   an estimate of the engine speed when the combustion event

27   occurs, can be set based on an inversion of the static

28   map, to give any desired combustion torque (Tcom) over

29   the next combustion event within the limits of the map.

30

31   In this new system, the use of the second input (ssMAP)

32   is effectively to control the amount of torque reserve of

33   the engine, the first input can immediately demand a

34   torque increase and it will achieve it (within the

1   limitations imposed by the static map), however the
2   second input must always be operating such that the
3   engine has the required amount of spare torque capacity
4   available. The distance, MBT-T (in units of torque) that
5   the engine is operating from its peak torque production
6   is again a static function of the engine speed, the spark
7   timing and the manifold pressure, or equivalently the
8   engine speed, the manifold pressure and the combustion
9   torque. I.e. MBT-T = f(speed, T_{comb}, MAP). This static
10 relationship may be linear in the variables or if not
11 will be smooth enough to allow linearisation for design
12 purposes. Note that since this path is not critical to
13 the cycle by cycle behaviour of the system, the effect of
14 any linearisation errors will be small. The manifold
15 pressure itself behaves in a non-linear dynamic way
16 affected by the secondary throttle, or electronic main
17 throttle, and the engine speed. This non-linear dynamic
18 behaviour can be separated into a linear dynamic portion
19 (when measured in the discrete, event based domain) and a
20 non-linear static map, the relationship between the
21 secondary throttle position and the distance from peak
22 torque being illustrated in figure 2a. The non-linear
23 static map can again be inverted and when the inversion
24 is used, the second output is now a linear function of
25 the second input (termed ss_MAP here), and the first
26 input and output. This is illustrated in figure 2b.
27
28 Detailed description of the preferred embodiments.
29
30 Since the combustion process is itself an inherently
31 event based process, the natural framework for a high
32 performance idle speed controller is in the (combustion)
33 event based discrete time domain. The following describes

1   the engine model formed as a result of the use of the

2   method described.

3   1) Since the combustion torque is a function of the spark

4   (which is set at least one control event prior to the

5   combustion event) and the manifold air pressure at the

6   end of the induction stroke, delays must be applied to

7   each input. For a four-stroke, four cylinder engine,

8   the manifold pressure delay is one unit.

9   2) The manifold pressure dynamics can be assumed to be

10   first order with fixed coefficient (although this

11   method would also include higher order models)

12 3) The engine speed then follows from simple Newtonian

13   mechanics.

14 4) The second output is a linear combination of the

15   delayed (desired) combustion torque, the delayed

16   manifold pressure and the speed.

17

18 The model for a four-stroke, four cylinder engine will

19 thus typically have four states, the delayed Tcomb, the

20 delayed ss_MAP, the manifold pressure and the engine

21 speed. The technology described here can also be used to

22 control engines with more or less cylinders, and with

23 faster or slower sampling rates by changing the model in

24 a way which will be clear to experienced practitioners.

25 The model description given above does not preclude the

26 use of the method described in a continuous time based

27 design.

28

29 When the controller so designed using the modified engine

30 system as described above is implemented, it would be

31 usual, although not necessary, to substitute more

32 accurate estimations of the torque map and actual

33 readings of the manifold pressure to calculate the second

34 output.

The values in the non-linear maps can be obtained by operating the engine in steady state at various operating points and measuring the torque produced at that point. For the secondary throttle, or electronic main throttle, to manifold pressure relationship, the secondary throttle, or electronic main throttle, can be opened in step increments and the behaviour of the manifold pressure recorded. Regression curves, look-up-tables or other mapping techniques can be used to perform the non-linear mappings.

The use of this method facilitates the use of several other techniques with an ease that was not available with prior art techniques. These include:

1) The use of feedforward torque estimates for known load disturbances. Since the input to the augmented system is combustion torque, if the load torque of a disturbance can be estimated, it can be cancelled by simply adding this estimate to the first system input. This eliminates the response time inherent in feedback systems and allows a potentially significant improvement in controller performance.

2) If the load disturbance can be delayed by a small amount (e.g. the air-conditioning is under the control of the engine management system and can easily be delayed by say 0.5 seconds before the pump is engaged) then the torque reserve of the engine can be quickly increased by changing the reference on the second input. Then when the load is engaged there is a lot of reserve torque available to reject the disturbance. Soon (e.g. 0.5seconds or less) after the load has been engaged the operating point can be moved back to a more

1   fuel efficient one. Items 1) and 2) can of course be

2   utilised together to get the benefits of both.

3

4   3) Sometimes it is desirable to spend time with the engine

5   efficiency decreased significantly from optimal, by the

6   nature of the method described above, this is trivially

7   easy to achieve. When the efficiency is reduced, the

8   'wasted' energy becomes thermal energy this may be

9   desired for other purposes. Two examples of this are

10   i)   After the engine has been started from cold it is

11   desirable to heat the catalytic converter up to

12   its normal operating temperature as quickly as

13   possible. By reducing the efficiency of the

14   engine, there is more thermal energy in the

15   exhaust gas that is transferred in part to the

16   catalytic converter.

17   ii)   When idling in cold climates, the energy being

18   transferred to the engine block may not be

19   sufficient to keep the heater matrix hot enough to

20   keep the passenger compartment comfortable.

21   Reducing the efficiency of the engine increases

22   the amount of thermal energy transferred to the

23   engine block and hence the heater matrix.

24   iii) When starting from cold, it may be desirable to

25   transfer thermal energy rapidly to the engine

26   block in order to quickly reach normal operating

27   temperatures and to enable rapid heating of the

28   heater matrix, facilitating fast warm-up of the

29   passenger compartment and defrosting/demisting

30   system.

31

32   It will be appreciated that the ability of the system to

33   compensate for a wide range of potential load

34   disturbances allows the running of the engine far closer

15

1 to optimal conditions for more of the time than with

2 previous techniques.   At the same time sub-optimal

3 operation is also possible where there is a requirement

4 to do so.

5

6 Modifications and improvements may be made without

7 departing from the scope of the present invention.

1   <u>Claims</u>

2

3   1.   A   control   assembly   for   a   non-linear   system
4   comprising a non-linear map interface means that
5   connects input and output points of a non-linear
6   system to a linear control arrangement.

7

8   2.   A control assembly as claimed in Claim 1 wherein the
9   non-linear   system   is   a   spark   ignition   gasoline
10   engine.

11

12 3.   A control assembly as claimed in Claim 2 comprising
13   an idle speed control system or an engine management
14   system of the gasoline engine.

15

16 4.   A   control   assembly   as   claimed   in   Claim   2   or   3
17   wherein the controlled inputs to the engine comprise
18   a   spark   timing   and   a   secondary   throttle,   or   an
19   electronic main throttle, and one or more settings
20   while the measured engine outputs comprise an engine
21   speed and a manifold pressure.

22

23 5.   An   internal   combustion   engine   management   system
24   comprising a provision for the control of engine
25   input parameters in accordance with an anticipated
26   load disturbance resulting from the operation of one
27   or more engine auxiliary components in advance of
28   the application of the said load.

29

30 6.   An internal combustion engine management system as
31   claimed in Claim 5 wherein the engine management
32   system controls both the engine input parameters and
33   the load disturbing components such that an engine

1 output torque is increased in accordance with the
2 increased load application.
3
4 7. An internal combustion engine management system, for
5 allowing the operation of the engine at close to
6 optimal efficiency in the idle condition, wherein
7 the system is further configured so as to decrease
8 the operating efficiency of the engine and increase
9 the thermal output of the engine in pre-determined
10 conditions.
11
12 8. An internal combustion engine management system as
13 claimed in Claim 7 wherein the increased thermal
14 output is required in a cold start situation, where
15 it is desirable to achieve normal operating
16 temperature as quickly as possible.
17
18 9. An internal combustion engine management system as
19 claimed in Claim 7 wherein the increased thermal
20 output is required in a cold start situation, to
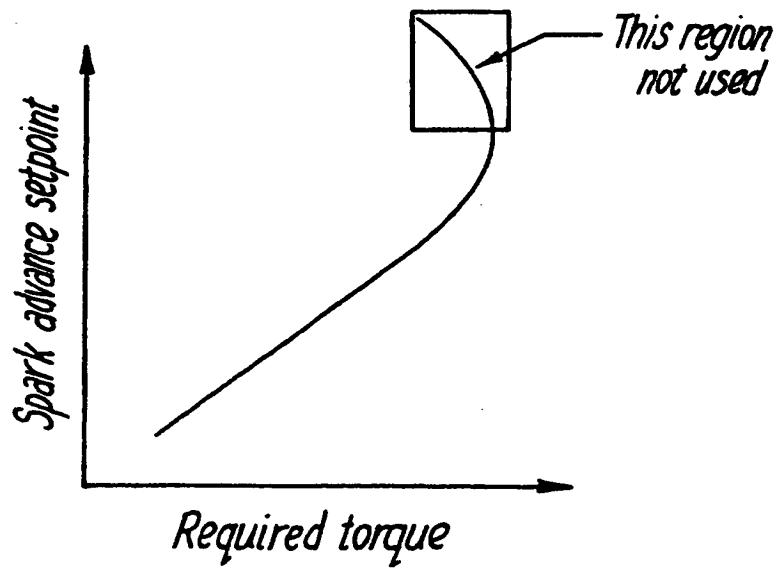21 allow a catalyst to reach operating temperature as
22 quickly as possible.
23
24 10. An internal combustion engine management system as
25 claimed in Claim 7 wherein the increased thermal
26 output is required in order to maximise the heat
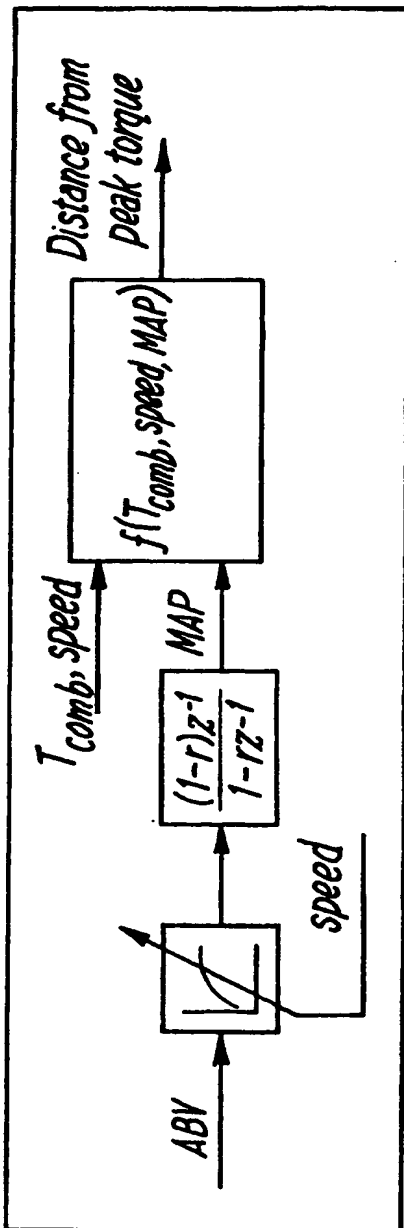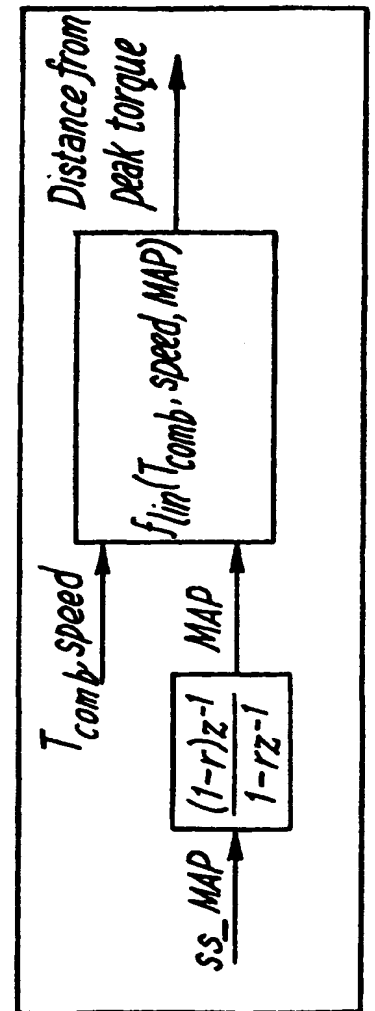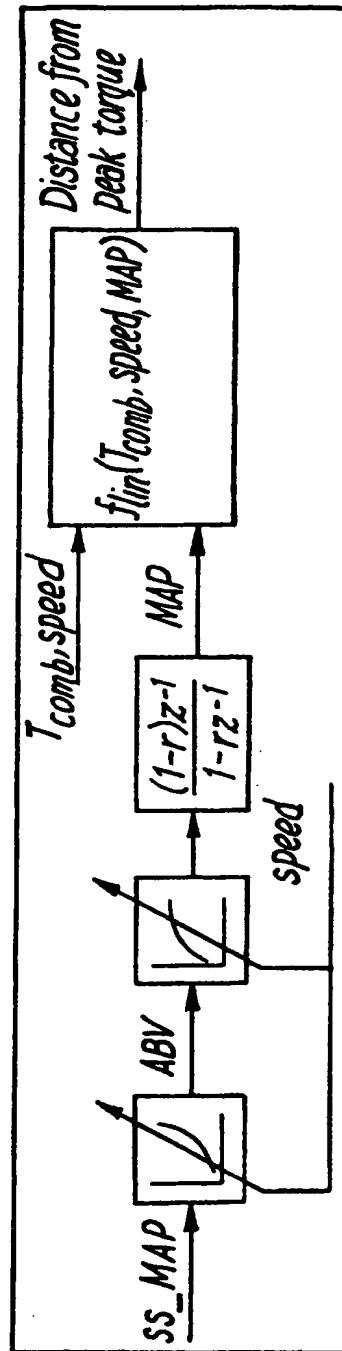27 output of an associated heating system.

Fig. 0

FIG. 1a

FIG. 1b

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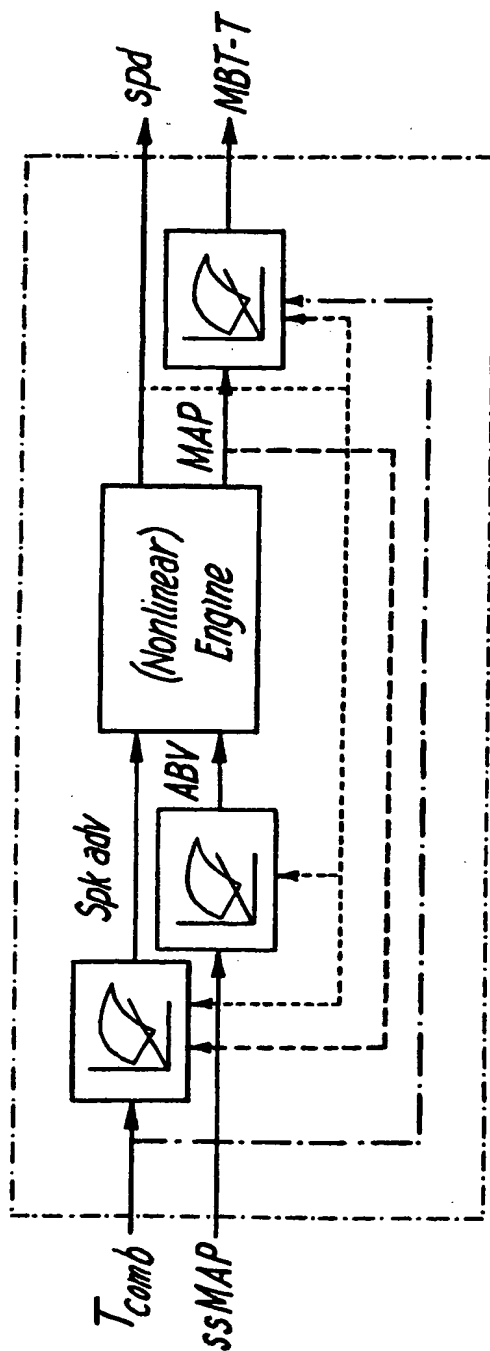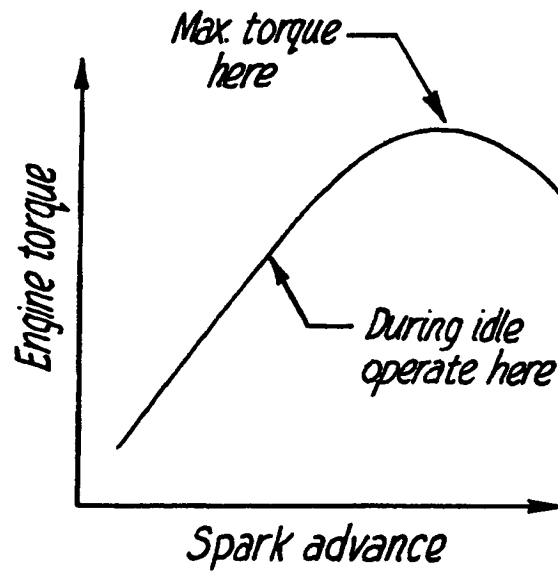
$$Fig.2a$$

$$Fig.2b$$

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INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER

IPC 7   F02D31/00   F02D37/02   F02D41/08   F02D41/06

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7   F02D

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category°	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 0 393 642 A (TOYODA AUTOMATIC LOOM WORKS ;TOYODA CHUO KENKYUSHO KK (JP)) 24 October 1990 (1990-10-24)	1-3
Y	column 2, line 17 –column 3, line 27 column 4, line 4 –column 5, line 5 column 5, line 41 –column 6, line 21 column 6, line 40 – line 48 figures 1,5	4
X	WO 97 28492 A (HARTKE ANDREAS ;HEINITZ DIRK (DE); SIEMENS AG (DE); PRZYMUSINSKI A) 7 August 1997 (1997-08-07) abstract page 2, line 9 –page 4, line 9 figures 1,2	1-3
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[X] Further documents are listed in the continuation of box C.   [X] Patent family members are listed in annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
7 August 2001	16/08/2001

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31–70) 340–2040, Tx. 31 651 epo nl. Fax: (+31–70) 340–3016	Libeaut, L

INTERNATIONAL SEARCH REPORT

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

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A	column 1, line 40 -column 2, line 16 column 3, line 61 -column 4, line 13 column 5, line 25 - line 31 column 5, line 48 -column 7, line 7	2-4

A	LIVSHIZ M ET AL: "NONLINEAR ENGINE MODEL FOR IDLE SPEED CONTROL" PROCEEDINGS OF THE CONFERENCE ON DECISION AND CONTROL. LAKE BUENA VISTA, DEC. 14 - 16, 1994, NEW YORK, IEEE, US, vol. 3 CONF. 33, 14 December 1994 (1994-12-14), pages 2449-2451, XP000679122 ISBN: 0-7803-1969-9 the whole document	1-6

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